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Microgrid Conceptual Design Guidebook | 2022

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NNSA National Nuclear Security Administration

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Conceptual Microgrid Design Guidebook

Acronyms and Definitions

Abbreviation	Definition
AEO	Annual Energy Outlook
ATS	Automatic Transfer Switch
CBECS	Commercial Building Energy Consumption Survey
DBT	Design Basis Threat
DBT	Design Basis Threats
DER	Distributed energy resource (e.g., solar photovoltaic installation)
DER-CAM	Distributed Energy Resources Customer Adoption Model
DOE	U.S. Department of Energy
DRC	A Grid Modernization Laboratory Consortium project titled Designing Resilient Communities
EIA	U.S. Energy Information Administration, Independent Statistics and Analysis
FERC	Federal Energy Regulatory Commission
ISO	Independent System Operator
MCDM	Microgrid Conceptual Design Methodology
MDT	Mircrogrid Design Toolkit
MER	Monthly Energy Review
O&M	Operation and Maintenance
PCC	Point of Common Coupling
PV	Photovoltaics
ReNCAT	Resilience Node Cluster Analysis Tool
RFP	Request for Proposal
RTO	Regional Transmission Organization

Abbreviation	Definition
SAM	System Advisor Model
SNL	Sandia National Laboratories
TMO	Technology Management Optimization
UPS	Uninterruptible Power Supply

GLOSSARY OF TERMS [1]

Community: Any group of stakeholders affected by the design, installation, and ongoing performance of a microgrid or system of microgrids intended to improve energy resilience.

Conceptual Design: An early-stage design that evaluates design options against system performance metrics at a high level to establish sufficient system understanding and predictability to enable planning and funding activities. It provides a reasonable estimate of the major elements, capabilities, and functions that a final design will have. This is generally considered a 15% design by architectural and engineering firms.

Critical Loads: Loads that correspond to the buildings/services that are critical to the community during an outage. Some critical loads are non-interruptible and will require uninterruptible power supplies (UPS) while other loads can endure limited periods of losses of electrical power. Critical loads need to be assessed and prioritized for each community based on site and community -specific conditions. Critical loads often require continuity of power through the duration of an outage.

Design Basis Threat (DBT): The design methodology uses DBT to define the most stringent conditions (threats) which must be met in the system design. These threats may be environmental (such as a hurricane) or man-made (such as a cyber or physical attack). The term is borrowed from the nuclear industry. The focus is on credible threats within a regional context, not necessarily only a local context.

Design Basis Outage: The outage duration and geographic extent determined by a given DBT.

Non-Critical Load: Those loads/buildings that are not directly necessary for public safety or survival, or critical military functionality. These loads/buildings can tolerate the Design Basis Outage.

Resilience Event: A low-probability, high-consequence event that exceeds electric reliability design parameters in magnitude, duration, or scale. The DBT quantifies specific, bounded resilience events to generate values and variables for use in design.

Blue Sky: Normal operating conditions. No threat to the system exists.

Black Sky: A DBT is active. The system has been impacted, is compromised, and resilience protocols are being deployed.

What to Expect…

This guide is meant to assist communities – from residents to energy experts to decision makers – in developing a conceptual microgrid design that meets site-specific energy resilience goals. Using the framework described in this guidebook, stakeholders can come together and start to quantify site-specific vulnerabilities, identify the most significant risks to delivery of electricity, and establish electric outage tolerances across the community. In addition to establishing minimum service needs, this framework encourages communities to consider broader sustainability goals and policy constraints and begin to estimate up-front costs associated with the installation of alternative microgrid solutions. The framework guides a community through data collection and a high-level assessment of its needs, constraints, and priorities, prior to engaging engineers, vendors, and contractors.

The first sections of this guidebook provide a high-level primer on electric systems. The latter sections include guidance for step-by-step data gathering and analysis of site conditions. The ultimate product resulting from the stepwise approach is a conceptual microgrid design. A conceptual design is defined as an initial design (10%-20% complete) that considers the specific threats, needs, limitations, and investment options for a given location.

Going through this exercise and developing the conceptual microgrid design as a community ensures the same community members who will ultimately live with the solution are the developers of its foundational design. Often, these are also the very same people who understand system tolerances and needs the best and are therefore the ideal candidates for establishing these criteria. Especially when it comes to evaluating critical infrastructure, it is the community that best understands the most critical services.

The framework is intended to facilitate a systematic approach to planning for resilience and provide a deeper understanding of how to use a framework to make decisions around microgrid solutions. Like many processes where tradeoffs need to be considered, this is often an iterative process. If this guide serves to help educate and empower communities who are beginning the process of deploying a microgrid, it has met the goal of its authors.

1. Introduction to Electric Power Systems and Energy Resilience

This module provides a general overview of a conventional electric power grid. In order to leverage microgrids to achieve electricity goals, integration with existing electric infrastructure is often the best approach. As we explore microgrids as means to improve energy resilience, we will look at the system as a whole. This section is intended to provide only a summary overview with basic terminology. For those seeking to study the electric grid more deeply, the U.S. Electricity Industry Primer [2] is an excellent resource.

1.1 Main Electric Grid

Most electric customers are served by a centralized **main electric grid**. For the purposes of this guide, main electric grids are defined as conventional, largely centralized systems with generation occurring at a large scale and often a significant distance from the customer. A conventional system is comprised of five components: generation, transmission, substations, distribution, and customers. See **Figure 1.** Across the United States and its territories, these can vary widely in sizes and service area characteristics, but all generally contain the same components.

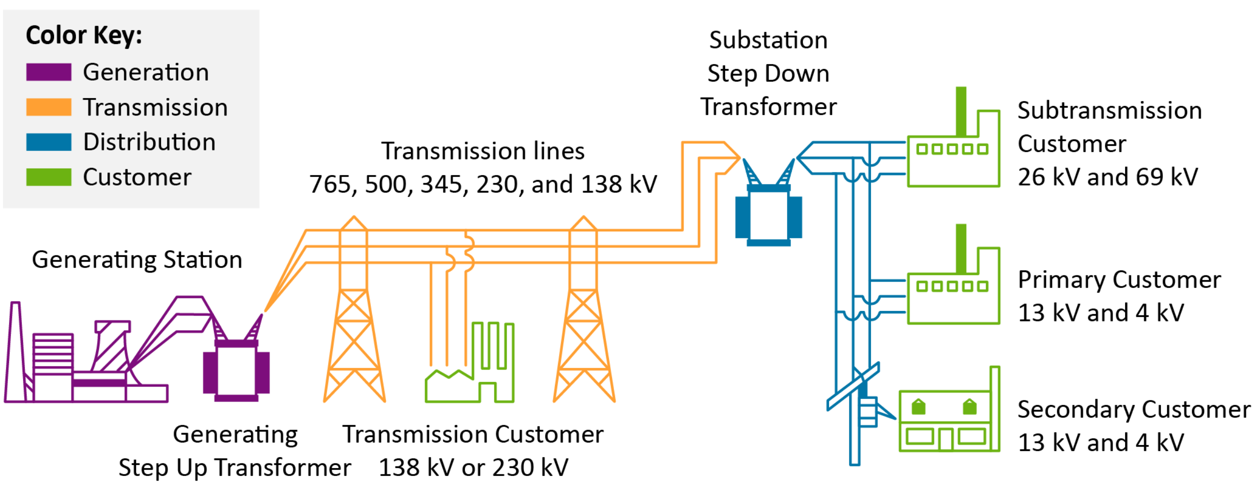
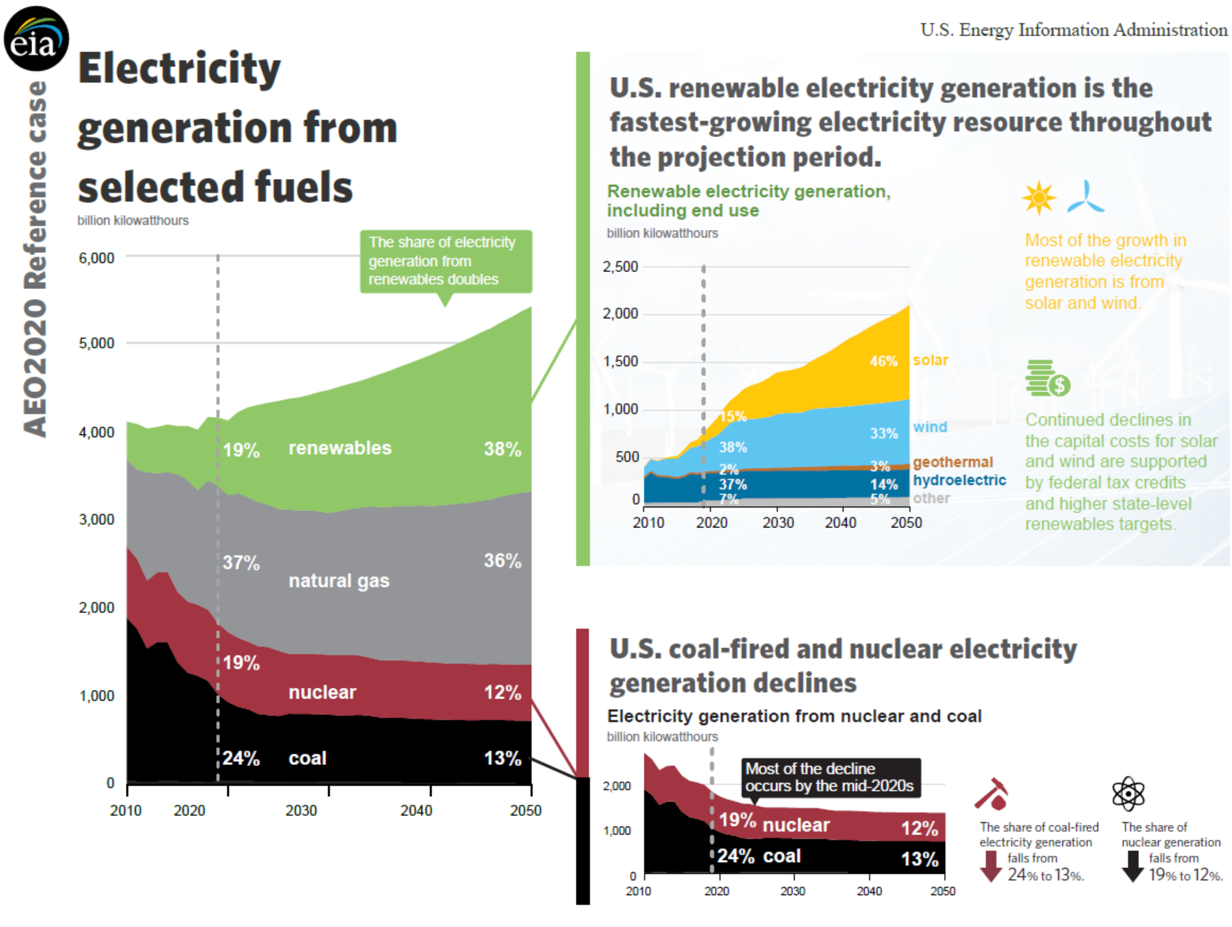


Figure 1: Basic components of an electric grid [1]. From left to right, this figure shows generation, transmission, distribution (leaving the substation), and customers.

1.1.1 ***Generation***

According to the U.S. Energy Information Association (EIA) [2]: "The three major categories of energy for electricity generation are **fossil fuels** (coal, natural gas, and petroleum), **nuclear energy**, and **renewable energy** sources. Most electricity is generated with steam turbines using fossil fuels, nuclear, biomass, geothermal, and solar thermal energy. Other major electricity generation technologies include gas turbines, hydro turbines, wind turbines, and solar photovoltaics." Although the fraction of total energy generated from renewable sources has expanded since 2010, domestic and global generation at a large scale remains heavily dependent on fossil fuels, as shown in **Figure 2.** As innovation in renewable energy and energy storage systems yields lower prices and easier implementation, as energy storage technology becomes more deployable, and in response to environmental pressure, the portfolio of generation is expected to shift away from fossil fuels.

Power systems are expected to experience increased incidents of disruption in the form of resilience events[1] in the not-too-distant future due to climate change. As society adapts to the changing severity and frequency of energy-disrupting events, such as hurricanes, floods, and fires, all parts of the power system may need to adapt, including by changing or augmenting the way power is generated. Generation, in addition to becoming more renewable to reduce its carbon footprint, may also become increasingly decentralized or **distributed**. Distributed energy resources (DER) are generation resources installed in a decentralized manner, located close to the customers they service and usually smaller in size. Decentralization can therefore support energy resilience since it protects against one failure in the energy system disrupting service to the entire system.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2020* (AEO2020) Reference case

Figure 2: Electricity generation by fuel source [21]

DER may be especially valuable to island and remote communities given geographic challenges to the supply chain. It is more difficult and more expensive to import material, fuel, and skilled workers to an island than it is to move these supplies around the mainland. DER generation in the form of specially designed solar panels, wind turbines, batteries, and reinforced generators, for example, may better withstand system shocks from natural and manmade disasters because generation occurs locally, and thus the geographic footprint of

[1] A low-probability, high-consequence event that exceeds electric reliability design parameters in magnitude, duration, or scale. The DBT quantifies specific, bounded resilience events to generate values and variables for use in design.

vulnerability is smaller than in a centralized generation configuration. Such renewable generation can further reduce dependence on imports. This guide focuses on microgrid design and DER for improved resilience, termed "black sky" value. But it should be noted that DER can provide value during "blue sky" days as well by working in concert with centralized generation even when there is no threat or outage. Considering this blue sky value in resilience planning is a best practice.

1.1.2 *Transmission*

Transmission includes the higher voltage (i.e., 115 kV and above) electricity delivery systems designed to transport energy over long distances with minimal power losses. These lines take electricity from the point of generation to substations where the power is typically reduced to lower voltages. Transmission lines often traverse multiple states and jurisdictions and are typically administered by a regional transmission organization (RTO) or an independent system operator (ISO). Careful attention is paid in transmission to balancing load and generation, maintaining a set frequency, and balancing the voltage between different phases.[2] **Table 1** shows typical voltage ranges for standard classification levels for power lines.

Power Line Classification	Voltage Range [kV]	Purpose
Ultra-High Voltage (UHV)	> 765	High Voltage Transmission > 765 kV; ultra-high-capacity lines
Extra-High Voltage (EHV)	345, 500, 765	High Voltage, Long Distance Transmission
High Voltage (HV)	115, 138, 161, 230	Typical Transmission Values
Low Voltage (LV)	<35	Distribution for residential or small commercial customers, and utilities

Table 1: Transmission classifications by voltage [3]

1.1.3 *Substations*

A substation houses transformers that connect the transmission system to the distribution system. Substations can provide multiple functions, but most commonly are used to *transform* incoming voltage to a different outgoing voltage. A substation might "step-up" the voltage from a generation source to transmission infrastructure. Another substation might then "step-down" the voltage so that it can be pushed to users through distribution infrastructure.

[2] For those interested in learning more about electricity transmission, the National Council on Electricity Policy has published a primer available here: https://www.energy.gov/sites/default/files/oeprod/DocumentsandMedia/primer.pdf

1.1.4 *Distribution*

Distribution systems consist of low voltage conductors/lines (i.e., 35 kV to 120V) that complete delivery of power to customers. Distribution lines, often called "feeders," originate at distribution substations, where the transmission lines terminate. Substations are designed to step the voltage down to customer use values. At a given substation, one will find protective equipment, switches, step-down transformers, and a distribution bus or busses. The substation reduces voltage from transmission to distribution scale, and distribution lines route low voltage electricity to commercial, residential, and industrial customers [3]. Distribution service transformers located within a few hundred feet of customers often further reduce the voltage to service levels (e.g., 120V). Electric utilities manage distribution feeders, ensuring that power is delivered to customers at consistent and safe voltage levels. **Figure 3** shows a typical pole-mounted configuration for a distribution line and associated components.

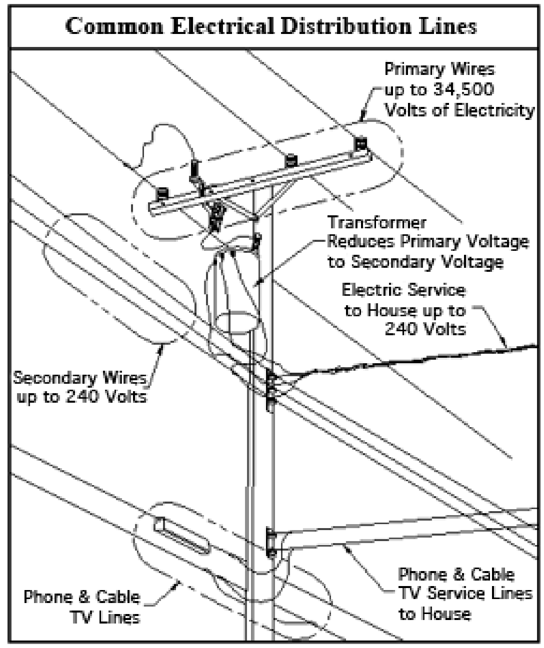


Figure 3: Common electrical distribution lines. [24]

1.1.5 *Backup Power*

Backup generators and/or uninterruptible power supplies (UPS) are another component in the power system usually located near the end user. These are often private assets, managed according to user preference without coordination with a local utility. Generators are often fossil fuel powered, whereas UPS are usually batteries. Backup power is installed to maintain critical loads for a limited period during a main electric grid blackout. Backup power design is a function of critical load and life-cycle cost parameters. "Roughly 95% of backup generators used by commercial buildings and critical facilities are powered by either diesel or natural gas [4]." These back-up power sources can be an effective way to improve reliability for short outages. But to improve resilience and mitigate vulnerabilities to longer-term outages, these types of back-up power are often insufficient and sometimes even problematic or dangerous if not properly maintained or operated. In many cases, even when adequately designed, backup generation is not reliable due to poor maintenance or insufficient fuel stores. Natural disasters such as hurricanes, floods, and tornadoes, as well as intentional attacks such as cyber or physical attacks to grid infrastructure can cause main grid outages lasting for weeks or more. Stored fuel for generators has a limited shelf life, and typically there is enough fuel on site to run generators for only a few days without external refueling from central storage sites through pipelines and transportation delivery infrastructure, and such sites and infrastructure may also be affected by an extended electric grid outage.

1.2 Introduction to Energy Resilience

Resilience has been defined by the Federal Energy Regulatory Commission (FERC) as a system's "ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event." This guide defines a resilient system as one that can endure or recover over an acceptable timeframe from large-scale events that impact electricity service to customers.

> The Federal Energy Regulatory Commission (FERC) has defined resilience as, ***"the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."*** -2018

It is important to understand the relationship between resilience and reliability. As **Figure 4** shows, energy resilience defines the holistic performance of a system in response to an outage-causing event. Reliability is a factor in resilience but is specific to commonly occurring power system disruptions. Whereas energy reliability is well defined and something utilities and stakeholders are familiar with monitoring and reporting, resilience is not. Reliability has been the functional requirement for power systems for decades. It is characterized by well-established metrics based on historical norms and predictive factors such as population growth, statistically "normal" weather events, and human error (e.g., car accident downs a power line). Reliability metrics are defined to account for foreseeable and previously experienced impacts. Resilience addresses the performance of the system in response to low-probability events outside the day-to-day experienced by the utility. For example, a vehicle taking down a power pole, due to its likelihood of occurrence and relative impact, is an event anticipated by and protected against as a normal function of system reliability. An extreme storm, however, falls outside of the scope of reliability. Thus, the mitigations required to withstand and recover from such an event fall into the category of resilience.

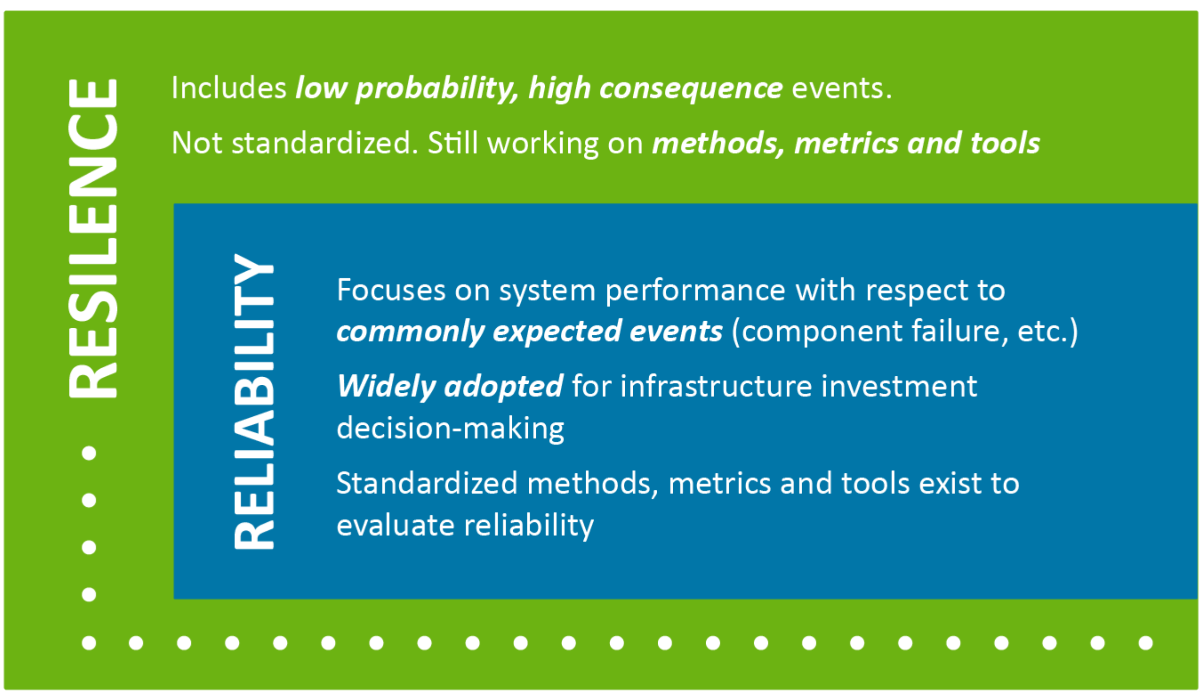


Figure 5: Relationship between Resilience and Reliability.

Resilience includes lower probability, higher consequence events and is assessed as a function of safety, security, reliability, sustainability, and cost effectiveness [4]. Resilience events result in extended duration outages. The longer the power is out, the more severe and life-threatening the consequences. The goal of any resilience investment is to reduce the ultimate consequences to the population, as shown in **Figure 5**. Even if the number of customers experiencing multi-day outages is small, the consequences to this subset of people can be catastrophic.

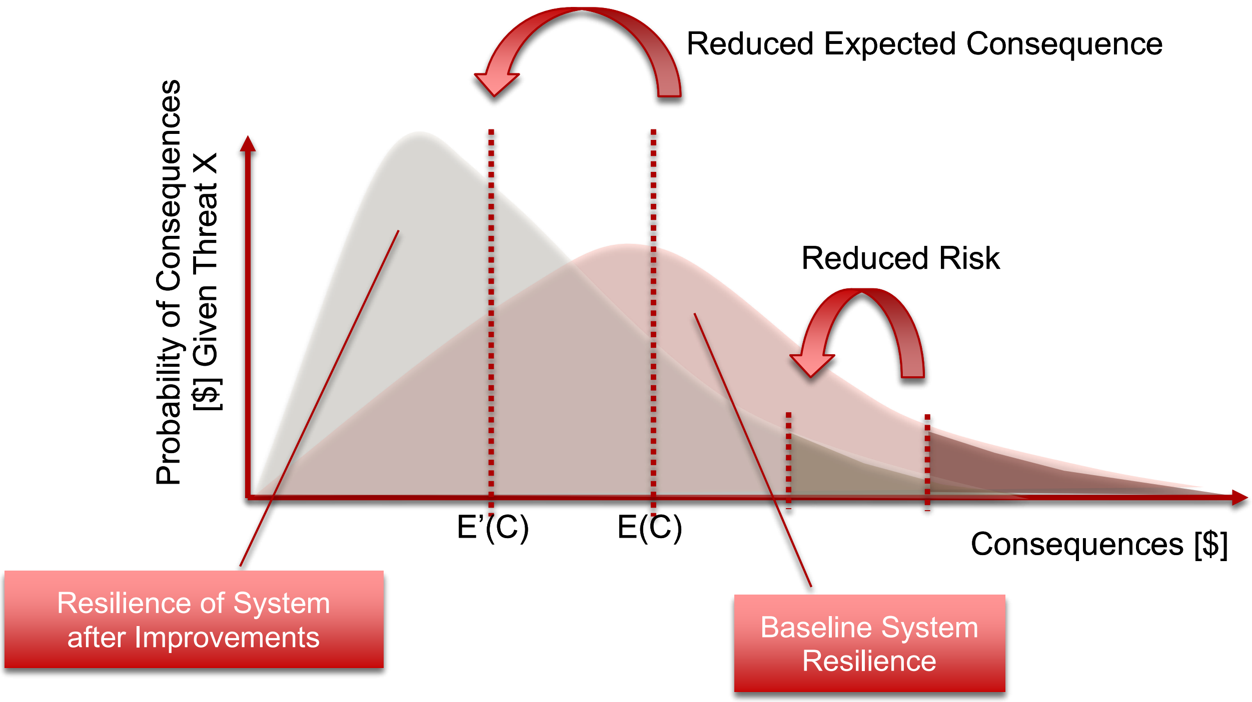


Figure 6: Resilience as a function of probabilistic threat and consequence reduction

Conceptually, resilience is intuitive and relatively easy to understand. But quantification of effective resilience measures has not yet been standardized. To successfully calculate a degree of resilience, one must quantify risk-associated consequences, recognizing that the threat may never be realized. This requires measurement of system components and baseline alternatives against probabilistic events, as well as an honest appraisal of system tolerances. Threats and consequences are discussed in detail and estimated quantitatively in the Conceptual Design section of this book.

1.3 Energy Resilience in Context

National and global trends indicate threat occurrences and magnitudes are increasing, a statistic that is all too familiar to a great many island communities throughout the world. "Since EIA began collecting reliability data in 2013, U.S. electricity customers have consistently experienced average total power interruptions of about two hours (106 minutes to 118 minutes) per year when major events are excluded. In 2017 and 2018, however, customers experienced nearly double this amount, driven by increases in interruptions with major events. In 2017, the average electricity outage duration with major events was twice that in previous years. This increase was largely a result of higher numbers of hurricanes, wildfires, and severe storms that year." [5] See **Figure 6**, for comparative interruption statistics collected nationally from 2013 to 2018.

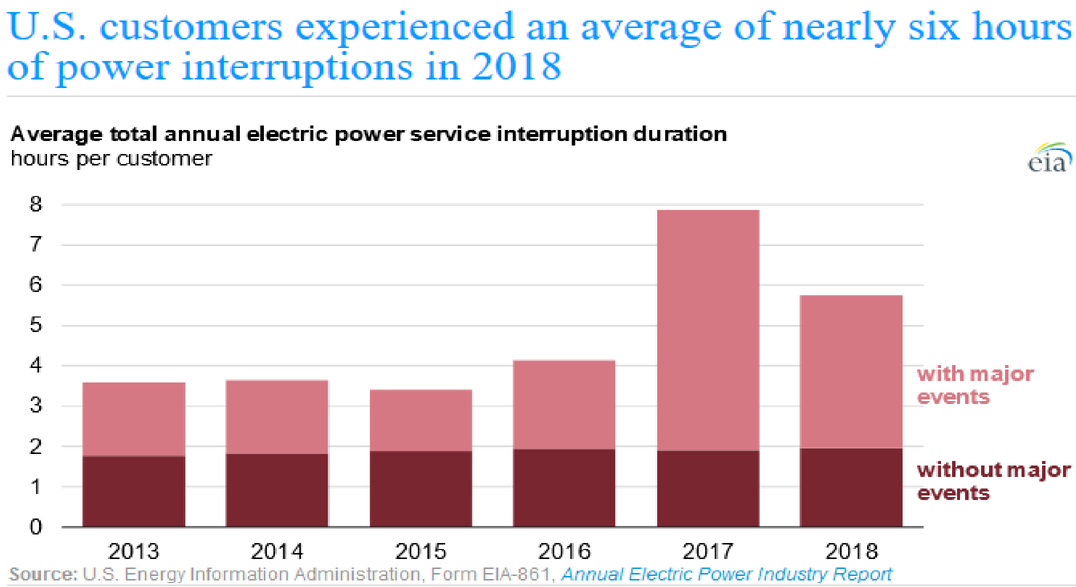


Figure 8: Average annual electric power service interruption 2013 - 2018

Threats, needs, and vulnerabilities vary from site to site. Generally, there are multiple ways to improve the energy resilience of an electric grid, including building additional transmission and distribution systems to provide energy supply redundancy, hardening transmission and distribution systems to make them more resistant to storms or attacks, and/or installing onsite energy generation and storage systems in the form of microgrids and nanogrids to protect critical loads. Optimizing a solution requires balancing the costs of resilience improvements against tolerable risk.

Since the late 1990s, research at Sandia National Laboratories (SNL) has shown that microgrids can provide a cost effective and practical solution to achieving energy resilience goals, especially microgrids at sites connected to the main power grid that can disconnect and still maintain functionality when the main grid goes down. Additionally, microgrids can alleviate some of the challenges associated with fuel demands when they incorporate renewable sources like solar (plus storage). Localized renewable generation reduces or eliminates dependencies on gas lines, fuel trucks, and other interdependent infrastructure that often fails during an outage. Microgrids can generally provide power indefinitely, whereas back-up generators typically have a limited production potential that is dependent on local fuel storage. In some cases, microgrids have added value in their ability to provide power back to the grid during blue sky days. Microgrids can provide a localized solution to the high costs of upgrading and updating the aging infrastructure across the country, though communities should explore multiple solution options against their design criteria. For example, leveraging a large generating plant located far away from load by undergrounding conductors could be a more effective solution depending on community goals, needs, and resources. This guide focuses on conceptual design of microgrids with the goal of empowering communities to evaluate the viability of this solution against other alternatives.

The following modules in this guidebook provide specific evaluation and conceptual design guidance for helping communities determine microgrid configurations that offer a viable, customized solution to site-specific energy resilience goals.

2. Energy Resilience Design Frameworks

This section is intended to be foundational to Section 4. Included here are two frameworks developed over the last 10 to 15 years as the Department of Energy (DOE) research community has gathered data and learned about processes, dependencies, and best practices, and as technology and the market has evolved.

Often, the best way for a group of energy stakeholders to determine an approach to a microgrid solution is to leverage a framework. A framework is a systematic approach that guides users step by step to support comprehensive design and planning. SNL developed the following frameworks to help provide stepwise structure to enable systematic approaches to complex issue resolution. The following framework discussion is intended to facilitate an assessment on the viability of microgrids as an energy resilience solution. Since these frameworks are to be used as guide, scrutiny by the user is encouraged. These frameworks are generic and apply broadly to "all" communities. No two communities are exactly alike, however, and so though a systematic framework may help guide a wide variety of communities, the activities occurring at each step will vary.

2.1 Designing Resilient Communities

The Designing Resilient Communities (DRC) Framework, see **Figure 7**, was designed to enable cities and utilities to align their investment planning for a more resilient electrical grid. The framework is implemented iteratively to account for feedback loops both within and across implementation processes (e.g., addressing technological issues in one planning horizon, which may shape and be shaped by addressing market or regulatory issues in another planning horizon) [7]. It is included in this guidebook for additional perspective on higher-level goals. This framework can be used to develop solutions for large populations with extensive stakeholder groups. It is not microgrid solution-specific and might result in resilience alternatives selection that includes a broad range of recommendations. This framework could be employed prior to moving into a conceptual design phase or could include conceptual design as part of an evaluation of alternatives.

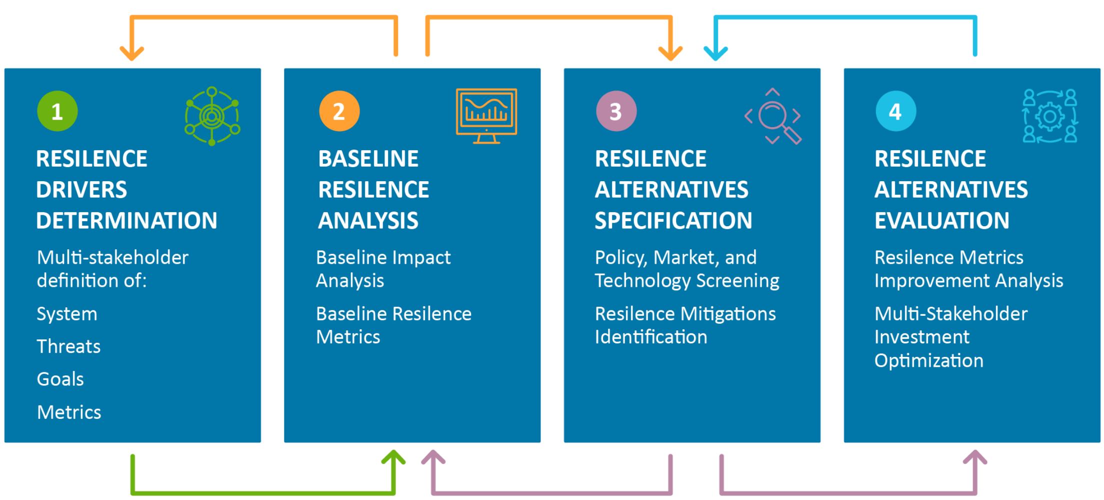


Figure 9: Designing Resilient Communities Framework

The four steps of the DRC Framework are defined as follows [6]:

1) *Step 1: Resilience Drivers Determination.* This step involves evaluation of multi-stakeholder input. During this step, the system is defined including its threats, the collective and individual goals, and, critically, the metrics necessary to evaluate proposed solutions. An important part of this step is the integration of pre-existing planning processes (e.g., city sustainability plan, utility integrated resource plan), and determining the role of resilience within these plans. Threats might be specific (e.g., natural, intentional/accidental, structural), or they might be general, (e.g., a 24-hour outage). SNL advocates investing the necessary time and analysis required to determine specifically what is lost when there is a power outage. For example, you might lose refrigeration systems, but are we keeping medicine from spoiling, or soda cold in a vending machine? When defining resilience goals, the goals should be as detailed as possible. Consider the existing system's ability to prepare, withstand, respond, and/or recover. The final activity associated with this step is identifying consequence categories (e.g., health, economic) and associated metrics (e.g., life expectancy, loss of assets).
2) *Step 2: Baseline Resilience Analysis.* The second step consists of the baseline resilience analysis. This step begins with historical data and/or simulations to probabilistically forecast disruptions from identified threats. These threats are then translated into specific system disruptions over a set timeframe. Having modeled the component, infrastructure, and multi-infrastructure impacts of potential disruptions, the baseline resilience metrics can be calculated. These baseline metrics will then be used during the next step to compare investments and actions being considered.
3) *Step 3: Resilience Alternatives Specification.* The third step involves identifying potential alternative investments to enhance resilience. The process begins with a screening of relevant technology, policy, and market conditions that could achieve the goals (e.g., resilience, sustainability, reliability) set forth during the planning process in Step 1. This step should also consider system constraints, such as regulatory frameworks and utility business models, which may be changing over time. SNL expects the initial implementation will focus on technology investment portfolios, which consist of technology solutions, potential planning, operational, and policy actions that enhance the system's ability to prepare, withstand, respond, and/or recover in accordance with site-specific goals.
4) *Resilience Alternatives Evaluation:* The final step involves evaluating the resilience alternatives specified in Step 3. Improvements in resilience metrics are evaluated by calculating consequence-focused performance metrics (repeating Step 2) and determining how these are impacted by the proposed mitigation alternatives (identified in Step 3). It is likely that there will be multiple stakeholders and multiple metrics, the prioritization of which is dependent on the perspective of the stakeholder. Final selection may involve negotiating weights for various resilience metrics with relevant stakeholders and prioritizing investment portfolios through multi-metric optimization. The objective is to leverage the framework to quantify decisions.

2.2 Microgrid Conceptual Design Methodology for Energy Resilience

The Microgrid Conceptual Design Methodology (MCDM) provides the foundation to Section 3. It is intended to provide a step-by-step approach to estimating the viability of a microgrid solution. A **conceptual microgrid design** is defined as the 10% to 20% solution. It includes a reasonable configuration and cost estimate for the needed generation, storage, distribution, operation, and management over the life of the system. A conceptual design uses available inputs, estimates, assumptions, and results in an approximation of an ultimate microgrid design. It is not a fully engineered, specified, or permitted design, but it provides enough detail to create a cost estimate, begin procurement processes (e.g., solicit requests for proposals (RFPs)) and identify regulatory challenges and opportunities – all of which are some of the requisite steps between the conceptual and final design. **Figure 8** shows the conceptual design in relation to a full engineered solution. It can also be instrumental in evaluating the financial viability and quantifying tradeoffs. This framework assumes that a microgrid has, through previous analysis, been identified as the appropriate mechanism for achieving resilience goals. It also leverages estimates rather than extensive due diligence in generating findings. It can be a powerful tool in helping communities understand the microgrid solution in terms of size and cost, and it can be helpful in comparing options and tradeoffs. It is intended to be reasonable estimate, and the process is intended to be intuitive, simplified, and straightforward. It should be reiterated that the efforts involved in getting from 20% complete to 100% complete can be substantial and are outside the scope of this guide.

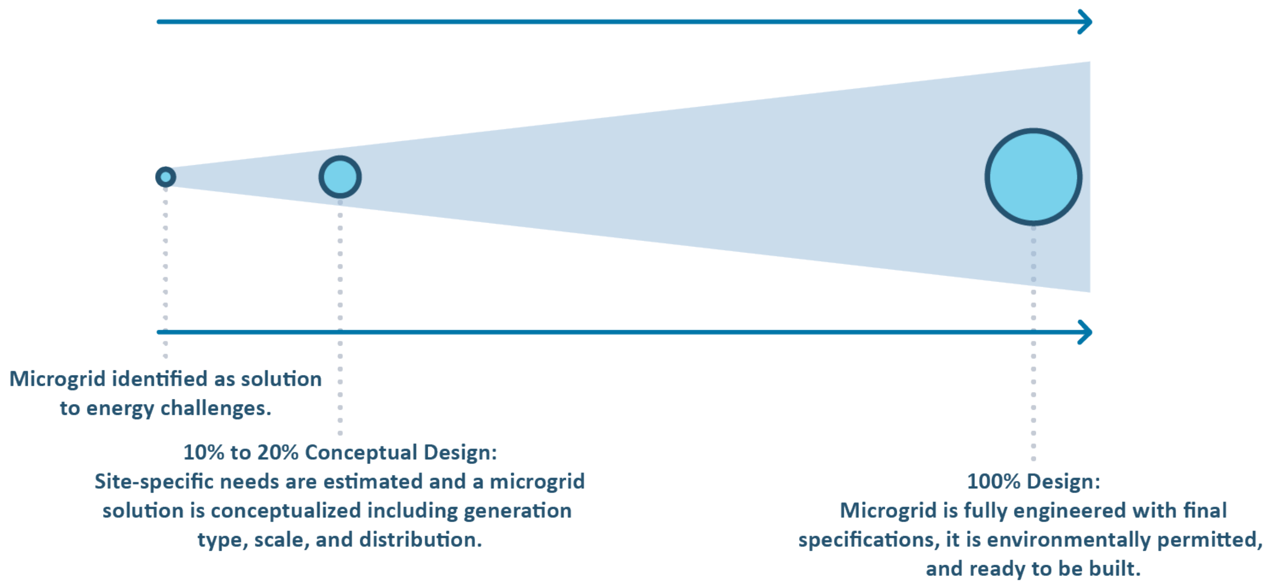


Figure 10: Conceptual design defined in relation to a fully engineered solution

The MCDM has **two main phases.** The first phase is designed to optimize data collection and analysis. It culminates with a description of the system. The second phase is the design phase which leverages the system goals and boundaries to iterate microgrid design solutions.

The steps described in **Figure 9** enable users of the framework to systematically gather the necessary data to estimate a microgrid design solution. Microgrid design options can be compared directly for cost and performance benefits relative to community-identified energy system performance goals. These steps are expanded and discussed in detail in the Conceptual Design section of this guide. This section is intended to describe the framework as it applies generally to microgrid consideration.

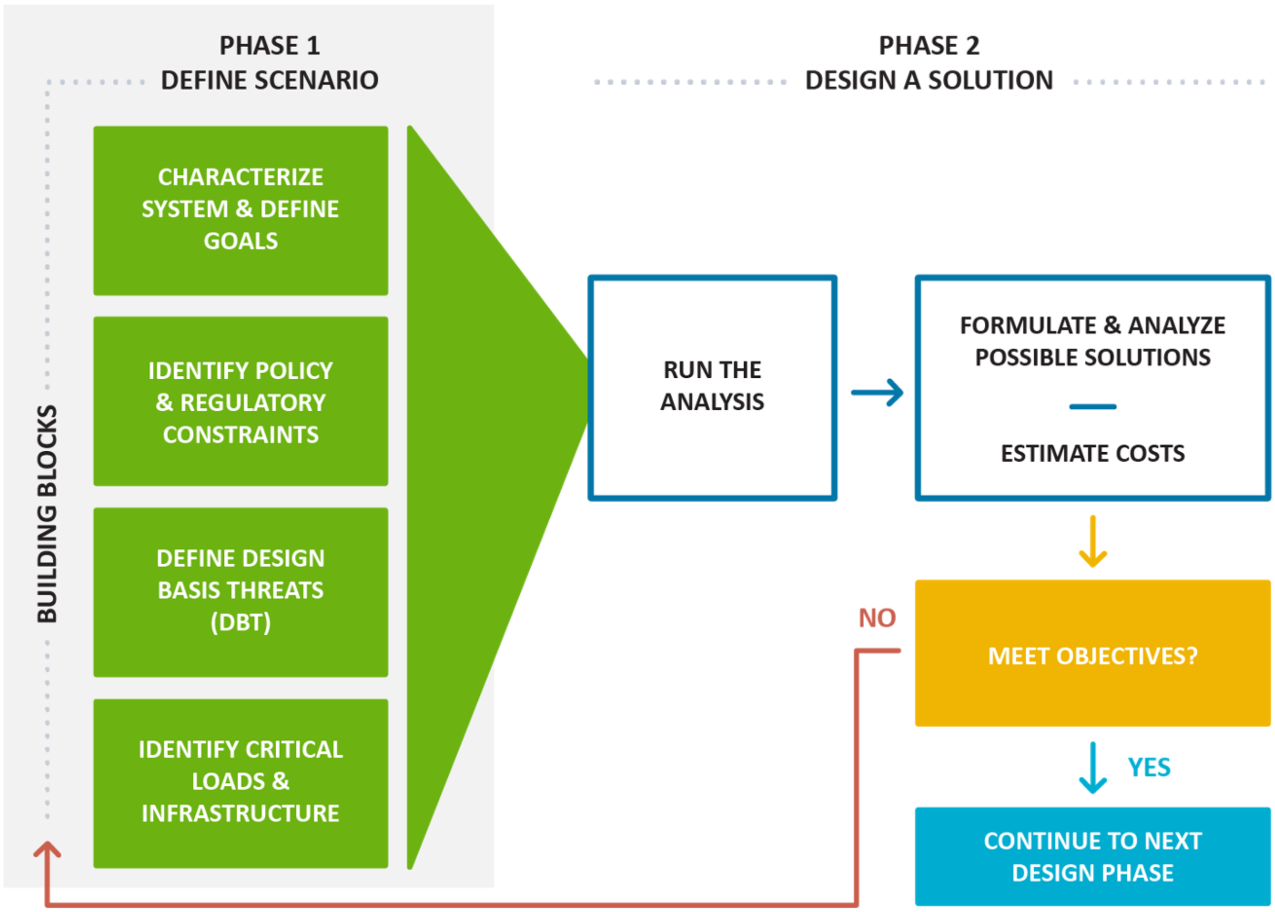


Figure 11: Microgrid Conceptual Design Methodology Framework Step-by-step Guide

A summary overview of the two phases of the MCDM framework are listed below. Each step is expanded further in the Conceptual Design Activity when these steps are put into practice.

Phase 1: Define scenario. This is a highly iterative phase with the sub-tasks shown in a general sequence, but the findings in any given area may require updating adjacent subject matter. The first step is to **characterize the system and define goals**. This phase results in establishing a boundary around the geographic extents. This phase also collects and refines overarching goals, both physical parameters as well as market and policy. Within the established boundary, the next step is to evaluate the infrastructure. Using various guides, best practices, and precedents, **critical loads and infrastructure** are identified and ranked in order of priority specific to the community. This step sometimes leads to discussion of infrastructure that is dependent on facilities or services that exists outside of the initial project boundary. For example, a water treatment facility existing outside the boundary might provide critical services to a hospital, shelter, or grocery store. This may warrant revision to earlier system boundaries. After the critical inventory assessment, the team will evaluate and define the **design basis threats** (DBT). This step is designed to identify the events to which the community is seeking to be more resilient. This step might reveal only one design threat, such as a hurricane or flooding. It might also reveal multiple threats, such as a natural disaster compounded by a cyber security attack. This effort often inspires revision to critical infrastructure inventory. For example, if flooding is determined to be the DBT, critical infrastructure outside the floodplain might be less vulnerable to outages. The final step in this phase of the framework is to evaluate **policy and regulatory constraints** specific to the system boundary. Relevant policy might include grid interconnection requirements, minimum percentage of renewable generation, or policy around distributed generation.

Phase 2: Design a solution. This phase takes the findings of the previous phase and quantifies a conceptual **microgrid layout**. A combination of **renewable and conventional generators** is analyzed to serve **peak load** values of critical infrastructure (or *all* infrastructure in some cases), and a system is defined. **Costs** are estimated and **performance** is evaluated. As described in detail in the subsequent Conceptual Design module, this will reveal viability, trade-off opportunities, and cost limitations. If the inputs afford no reasonable conceptual path forward, the team can return to the previous phase and reevaluate the data.

3. Microgrids for Resilience

This module is intended to provide a general overview of modern microgrid configurations, sizes, and technology. When designed properly (and managed well, a subject that is critical to microgrid success but beyond the scope of this guide), microgrids provide a viable solution for a breadth of challenges. They can be used to accommodate a wide range of load profiles and can be configured to the custom needs of a given area. As described in the subsequent sections, microgrids can be small or large, stand-alone or integrated, advanced or simple, and powered by almost any fuel source [7].

3.1 Microgrids: Sizes and Types

We define a microgrid as a group of interconnected loads and distributed (localized) energy resources that act as a single controllable entity. A microgrid can operate in either grid-connected or island mode (including entirely off-grid applications) [8]. A microgrid can span multiple properties, generating and storing power at a dedicated/shared location, or it can be contained on one privately-owned site. The latter condition, where all generation, storage, and conduction occur on one site, is called "behind-the-meter."

Microgrids come in a wide variety of sizes. **Table 2** shows common ranges at the associated level of service that can be achieved. There is no established limit, however. Behind-the-meter installations are growing in size especially as entities like hospitals[3] are installing their own systems. Where these once served a single residence, they now power entire commercial complexes. **Table 2** includes ranges to provide scale and represent historic values.

System	Common Sizes Considered[4]	Common Attributes	Scale
Microgrid	~500kW to 20 MW	Medium voltage, 4kVA to 34 kVA, 3-phase infrastructure. Interconnection location is typically in front of the utility meter.	~50 to thousands of homes and/or commercial and industrial sites, depending on a multitude of factors
Microgrid- Behind the meter	~5kW to 5 MW	Could be low or medium voltage. Could be single- or three-phase infrastructure. Interconnection location is behind the utility meter.	~1 home up to a few buildings

Table 2: General Microgrid Generation Capacity

[3] https://microgridnews.com/kaiser-microgrid-provides-hospital-safety-and-reliability/

[4] There are no pre-defined minimums or maximums, but these ranges show a typical size range. The variability results from a dynamic environment with shifting boundaries.

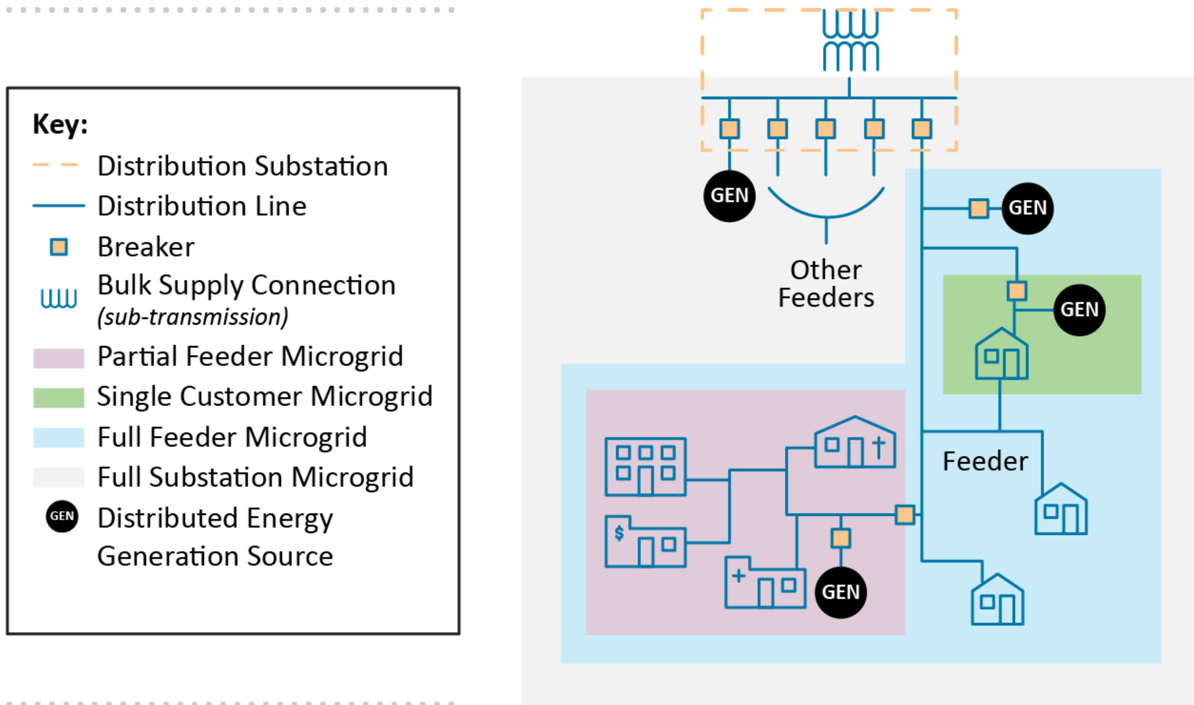


Figure 12: Illustration depicting the various possible configurations of microgrids [23]

As shown in **Figure 10,** microgrids can provide power to a single customer or a full community. In cases where the microgrid is built into existing distribution infrastructure, configuration can be a function of segments of the distribution lines or "feeders." They may serve several customers as a partial distribution feeder microgrid or may encompass a full feeder or substation. The flexibility in size is a benefit of microgrids, which can be designed around the goals of a given project, site-specific fuel sources, and space availability, as well as the configuration of critical loads and population needs.

The basic operation of a microgrid can be characterized based on:

a) whether the microgrid is connected to the main electric grid or islanded, and
b) if the microgrid has enough generation for sustained operation or is designed for shorter-term, intermittent backup generation only.

These operation characteristics result in three basic types, which are listed here and expanded upon below:

- Type 1: Microgrid for Backup Only
  - Operates only when the main electric grid is down
  - Generation is sized to cover critical loads only
- Type 2: Always Islanded Microgrid
  - Never connected to the main electric grid (e.g., a remote system far from the main grid)
  - Has enough local generation to cover all local load
- Type 3: Hybrid Microgrid
  - Operates grid-connected part of the time and islanded part of the time

    - Operation mode determined by factors including costs, main grid outage, fuel supply, etc.
  - Has enough local generation to cover all local critical loads, at minimum

Type 1 microgrids are designed to provide power as back-up only; they do not operate when the main grid is available. Loads served by Type 1 microgrids are typically limited to critical infrastructure. During an outage Type 1 microgrids are islanded from the main grid by opening a point of common coupling (PCC) main breaker; additional switching may be implemented to isolate the critical loads, leaving the non-critical loads de-energized. While the simplest Type 1 microgrid would be one generator and one critical load, these microgrids can be designed to incorporate multiple generators and fuel sources, and to serve multiple critical loads. In some cases, extra generators are used to provide redundancy. Control schemes vary in these types of microgrids, often related to the number of generators employed. Coordinated controls can allow multiple generators to provide more efficient, reliable, and resilient backup power.

Type 2 microgrids are never connected to the main grid. These systems may be referred to as off-grid or stand-alone. Type 2 microgrids are held to the same reliability standards as main grid service, designed to accommodate the continuous, full load for all users. Type 2 microgrids usually require larger generation resources, fuel supplies, and energy storage systems than Type 1 or Type 3 microgrids, since they must constantly operate autonomously. Although there is no PCC switch needed for isolation from the main electric grid, Type 2 microgrids often have internal isolation switches to separate critical loads from non-critical loads during periods of low generation (e.g., due to a fuel shortage or a lack of wind or solar resources).

Type 3 microgrids can operate either grid-tied or islanded from the main electric grid. Type 3 microgrids will generate enough electricity to cover critical loads at a minimum, but capacity should be maximized within project limits. Flexibility increases with capacity enabling the microgrid to be used as a tool not only for resilience but also to respond to grid signals such as time of use pricing, demand response requests, or, in some cases, generating revenue. During times of high microgrid load, the microgrid may draw power from the main electric grid to supplement its local generation. During times of low microgrid load, it may be possible to sell power back to the main grid. Sending power back to the main grid may be particularly valuable during periods of main grid peak load and during resilience events, which stress the main grid.

Note: In this guidebook, when we mention "microgrids" we are typically referring to Type 3 microgrids.

4. Conceptual Design Activity

This section is designed to generate a conceptual design and initial cost estimate for a site-specific microgrid. The conceptual microgrid is designed to about 10-20% completion, providing a general description of the major design and construction elements, likely siting of major components, and suggestions of the elements and operational scenarios to be included based on estimated loads. The conceptual design can be used to communicate plans to funding authorities and/or to provide an architectural and engineering company enough information to develop a preliminary engineering design.

4.1 Foundational Design Elements

The elements foundational to a sound design include consideration for *safety, security, reliability, sustainability,* and *cost effectiveness.* It is important to understand and define these for a given set of goals and within a specific jurisdiction. There are inherent tradeoffs within these design elements that need to be understood and defined to optimize any design to a given community's needs.

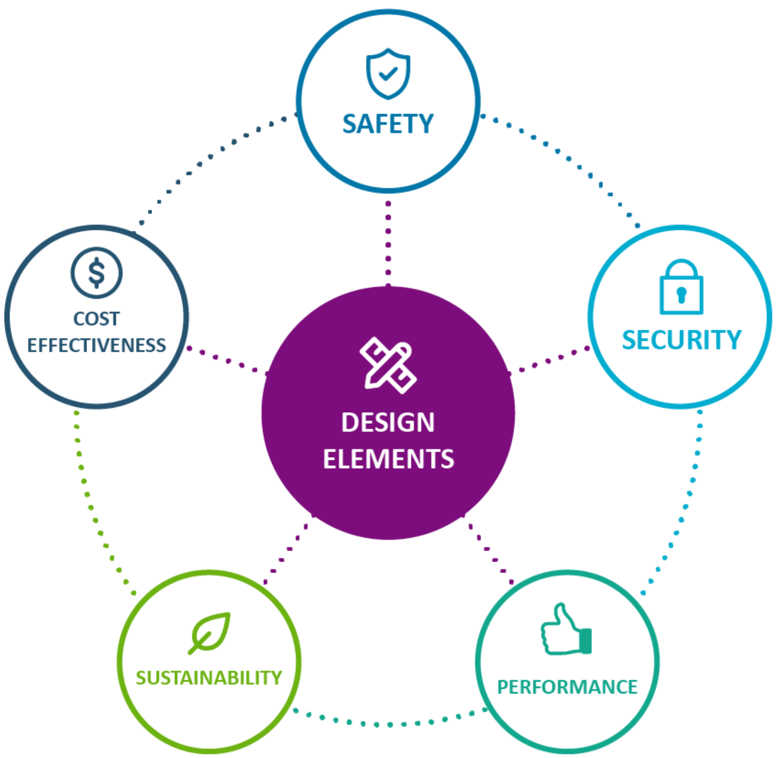


Figure 13: Pillars of microgrid design

The first attribute, *safety*, ensures that energy is provided to the end user in a safe manner. This means that the energy system must function well even when components fail and must be developed with safety as a top concern.

The second attribute, *security,* makes a power system robust to direct intentional threats, whether they be cyber or physical. Security can be accomplished in different ways, for example through hardening of the energy infrastructure or by having more redundancy in energy systems.

The third attribute, *performance*, reflects a power system's ability to meet its electric demands. Performance can be considered from a "blue sky" perspective, when there is not a major, low probability event causing an outage and systems are operating in a normal environment, as well as during a "black sky" event, when a threat has been realized and a high consequence outage exists. Although it may be impossible to ever achieve 100% performance for all buildings and functions during an extended outage, serving critical power needs is necessary for public support and safety.

The fourth attribute, *sustainability,* includes both internal (system functionality over the design life) and external (its cumulative impact on the external environment) considerations. Sustainability defines the ability to operate a power system not only for a designed duration, but in a manner that will not compromise the future (e.g., the environment) and does not present ongoing maintenance or economic challenges. Sustainability can be improved with the use of onsite energy resources, including renewable energy, to achieve environmental sustainability, such as photovoltaics (PV), geothermal heat pumps, and combined heat and power. Renewable resources can also simplify supply chain vulnerabilities (fuel supply) and minimize preventative maintenance.

The fifth attribute, *cost effectiveness,* relates to the reality that not all energy systems can achieve perfect resilience given cost constraints. Affordability includes evaluation of the costs of different energy infrastructure upgrade options relative to the benefits of site-specific factors including higher reliability, and extended outage capability improvements.

4.2 Phase 1

Phase 1 of the MCDM (**Figure 12**) is designed to collect and organize the information necessary to evaluate a microgrid solution. This framework ensures two important things: adequate understanding of the system, and clearly defined stakeholder goals. Investing effort to collect and curate this information will be important to the integrity of the analysis performed in Phase 2.

Figure 14: Phase 1 of the Microgrid Conceptual Design Methodology (MDCM)

CHARACTERIZE SYSTEM AND DEFINE GOALS

It is important to establish the initial energy system boundaries to be evaluated in the microgrid design, including the geographic boundaries and what stakeholders are implicated. This step requires deliberation and discussion of the motivation for the microgrid development, types of events and outages that should be considered, and the major critical functions and capabilities that the community needs from the microgrid during an outage.

A community may be as small as a few neighbors creating a small microgrid or as large as an entire city looking to build a large microgrid or a system of microgrids to serve its residents.

Steps to define energy system boundaries include:

- Determine initial boundaries for the size and scope of the power system to be addressed. Considerations include:
    - Boundaries, which may be a campus, a military base, or a whole city/town.
    - The distribution system configuration as an existing set of boundaries – feeders, substations, switchyards, etc.

- Based on the boundaries, determine the key stakeholders who should be involved in the MCDM process, such as (this list is not comprehensive):
  - City government or base/campus operators
  - Public works
  - Utilities (power, gas, water, communications)
  - Community organizations
  - Schools
  - Local businesses and services
- Evaluate existing conditions:
  - Identify what electric utility system data exists, especially data that can be related geospatially to critical infrastructure connections
  - Historical outage data
  - Demographic information (e.g., census data, population density, etc.)
  - Development plans
  - Funding limitations and criteria

BEGIN TO **CHARACTERIZE SYSTEM AND DEFINE GOALS**

Evaluate:

- What is the geographic footprint?
- To what types of services and assets do we want to provide energy resilience?
- For what duration of time (days, weeks, longer) do we want to provide these services and assets? **This will also be discussed in the DBT section.**
- In addition to existing backup generation, what types of distributed resources should we consider (e.g., diesel, gas, generators, cogeneration, renewables like PV or wind, etc.)?
- In addition to providing emergency services, do we want to consider ancillary benefits like cogeneration, providing peak shaving, selling power back to the utility, any other goals or local initiatives?
- What funding sources are available (federal, city, state, private purchase agreements, etc.), and are there requirements associated with these?

CRITICAL LOADS

This module provides a general discussion of how to determine critical loads. These are the loads that *need* to be served. This will establish a minimum size (capacity) for the microgrid. This step can be very difficult as there are few loads that are not critical to someone, and tradeoffs will force hard decisions. It is important to remember that there is no one-size-fits all prioritization scheme and that communities will have to seek input from a broad cross-section of stakeholders to develop an accurate account of critical loads. This section is intended to systematically evaluate critical load using federal sector definitions (see **Figure 13**) and a customizable rubric developed by SNL that enables quantification of assets. This step requires key stakeholders to discuss their expectations of the microgrid, and to understand interdependencies (e.g., communications infrastructure requires power and power infrastructure requires communications). The goal of this section is to enable stakeholders to rank the major critical functions and capabilities needed from the microgrid during a main grid outage based on scenario assumptions including duration(s), as well as to estimate load demands.

Figure 15: Federal Critical Infrastructure Sectors [9]

Many facets of modern society are heavily reliant on the main electric grid, and a major outage for an extended duration can have severe consequences. Several other categories of infrastructure, including water, transportation, and communications are heavily dependent on electric power infrastructure. Loss of these services can lead to cascading impacts to healthcare, emergency operations, command and control centers, municipal services, basic human services, and more. It is important to be systematic in this analysis so that decisions made about the microgrid design are comprehensive.

> *"The Nation's critical infrastructure is diverse and complex. It includes distributed networks, varied organizational structures and operating models (including multinational ownership), interdependent functions and systems in both the physical space and cyberspace, and governance constructs that involve multi-level authorities, responsibilities, and regulations. Critical infrastructure owners and operators are uniquely positioned to manage risks to their individual operations and assets, and to determine effective strategies to make them more secure and resilient."*
> PRESIDENTIAL POLICY DIRECTIVE/PPD-21, February 12, 2013

As part of a microgrid conceptual design assessment, we ask communities to identify critical needs, critical operations, and critical functions they believe need to remain in operation for a range of events that could vary in severity and duration. Though actual performance goals and resilience capabilities needed for a community vary, general categories of operational services have somewhat standardized definitions. A general discussion of services that need to be considered are included in the upcoming exercise. For more complex systems, interdependencies should be evaluated**. Figure 14** shows a diagram of such analysis.

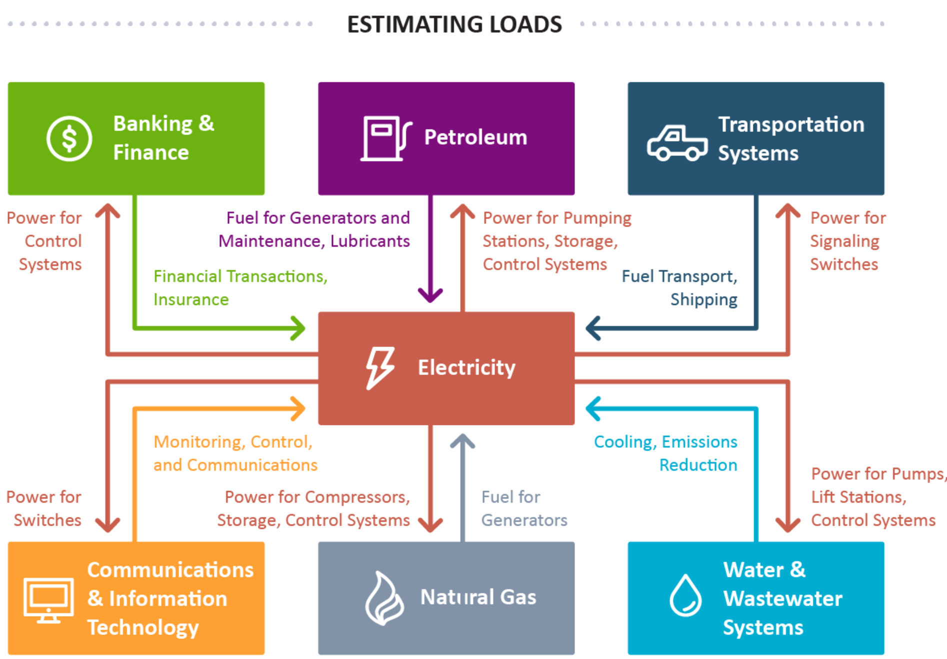


Figure 16: Simplified electricity service interdependencies diagram [22]

Quantifying demand at critical loads is an important part of assessing system needs. The best source for this information is often the power utility. Data that shows 24-hour demand curves throughout the year enables a refined assessment. In cases where load data cannot be provided, an estimate needs to be made. The EIA Commercial Buildings Energy Consumption Survey (CBECS) is one such resource; it provides reasonable per-square-foot estimates for standard commercial buildings. See **Figure 15.** Note that this data is developed from a national survey. Site-specific factors could be considered at locations known to vary from average estimates. Further, this survey does not provide load profiles, which can be critical to balancing generation and storage against renewable resources. There are other ways to estimate values that might be provided by the utility or other sources that should be explored to establish best estimates. Other sources that might be useful in estimating building energy estimating include: the EIA Annual Energy Outlook (AEO) or Monthly Energy Review (MER), EPRI data, the DOE Building Performance Database, or federal commercial building information, such as the U.S. Environmental Protection Agency ENERGY STAR Portfolio Manager.

It can be difficult to incorporate the **social benefit** of a given load, but it is important to consider that not all areas within the outage area will suffer equally upon power loss. Disadvantaged and vulnerable communities will have to work harder sooner after an event than those with more resources. Equitable evaluation of the system requires deeper understanding of the people within. To the degree possible, critical loads should be a function of their maximum social impact.

Figure 17: Snapshot of Commercial Buildings Energy Consumption Survey (CBECS) Data

EVALUATE THE **CRITICAL INFRASTRUCTURE** PRIORITIZATION

Develop a rubric for evaluating critical infrastructure. See **Appendix B** for a sample worksheet that lists and ranks critical services for a sample community. Consider outage duration as a factor in critical ranking.

Community outreach, education and engagement are paramount when microgrids are sited and sized and should be conducted early and often to: get input and feedback; conduct needs assessments; and evaluate locations, hubs, features and overall impact for enhanced resiliency and equitable outcomes.

DESIGN BASIS THREAT

The DBT can be used to design a microgrid for a specific resilience scenario. It defines the threat(s) exposing excessive vulnerabilities in the electric grid. This is a highly localized analysis based solely on the parameters unique to the design area. A given DBT will impact a system in terms of both the consequences, expressed as power loss, equipment loss, and economic loss, and the broader potential threats to public safety, which may not be equitably experienced. Additionally, a given DBT will have a duration associated with how long the threat is expected to last, and how long it will take to restore the system and recover from the threat. In many cases it is difficult to define the impacts and duration of a DBT, since the threat may occur rarely (such as hurricanes, earthquakes, etc.) or may not have previously occurred at all (such as cyber-attacks). For these, a reasonable worst-case estimate can be used. It is important to distinguish key threats and to attempt to rank them. It is also important to determine the key threats that should be specifically designed-for or prioritized (due to common occurrence and/or high impact) and which ones can be ignored (due to low impact and/or extremely rare occurrence).

This module provides a general discussion of how to identify potential DBTs, differentiate between the consequence associated with each, and utilize this knowledge to evaluate which DBTs should most inform and influence the microgrid design. The goal is to quantify and address impacts to performance objectives. Performance objectives should be separately listed for each DBT (e.g., continuous operation, back online within two hours, etc.). A list of common DBTs is included in **Table 3.** Each threat may result in a range of outage potential. Probabilistic analysis and known system vulnerabilities (e.g., infrastructure in the floodplain) should be used to estimate extents and durations. Historic events can also be very helpful in predicting consequences, even if observations were largely qualitative.

Design Basis Threat Examples		
Natural	**Direct Intentional**	**Structural/Other**
Ice, snow, and extreme cold	Cyberattack	Economic/Market Shocks
Extreme heat	Electromagnetic Attack	Regulatory/Policy Changes
Hurricanes, tornadoes, and monsoons (wind)	Kinetic/Physical Attack	Aging Infrastructure
Flooding, storm surge		System Complexity
Earthquake		Geomagnetic pulses
Tsunami		Capacity constraints
Wildfire		Workforce turnover/loss of institutional knowledge
Drought		Dependencies and supply chain interruptions
		Human error

Table 3: Example Threats to Energy Resilience

The DBT provides boundaries on the environment in which the system must be made more resilient, sometime called the "impact zone." It is a cooperatively developed statement(s) that explains the threat or combination of threats (such as a hurricane, flood, and/or cyber-attack) and provides a basis for the design.

It is possible to design a threat-agnostic system that functions according to generalized system performance goals, in which case the analysis is more “blue sky.” This approach often reveals day-to-day benefits and can help quantify longer term, big-picture impacts.

BEGIN ASSESSMENT OF **DESIGN BASIS THREATS**. COME OUT OF THIS STEP WITH PERFORMANCE GOALS IN RESPONSE TO DESIGN THREATS.

Evaluate:

- Natural, manmade, and other threats – make comprehensive list from which to select design parameters.
- Likelihood v. severity
- Look at maps and other material to evaluate consequences (e.g., flood mapping, risk indices, news reports)
- Consequence-based evaluation (i.e., what do we lose, and who loses it, when we lose power)

POLICY AND REGULATORY CONSTRAINTS

Current and proposed policy relevant to the area of interest should be collected and evaluated. It is important to engage the right expertise and stakeholders to ensure that assumptions about allowable technologies, interconnections, planned revenue streams, permitting processes, tax incentives, and other potential driving factors are fully assessed. This information can be aggregated and categorized, creating inputs and limits for subsequent analysis and optimization. Specific examples might be found in renewable penetration standards, emissions reductions, or electrification-of-fleet goals set forth by the state, city, or municipality.

CAPTURE THE **POLICY AND REGULATORY CONSTRAINTS** WITHIN THE JURISDICTION OF THIS MICROGRID LOCATION

Evaluate:

- Regulatory requirements and limitations to grid-tied microgrids (e.g., Puerto Rico "Microgrid Rule" 75% to be independent of PREPA ← will determine footprint)
- Consider audience: utility, regulator, developer
- Consider funding requirements if known

4.3 Phase 2

After Phase 1 of the conceptual design process, sufficient inputs exist to begin evaluating possible solutions and available computational toolsets. There are a host of tools developed by the U.S. DOE and the national laboratory complex designed to support this effort. **Section 6** of this guidebook lists several. We will discuss relevant tools during the exercise portion of this phase. The guiding framework for developing solutions based on established parameters is shown in **Figure 16**.

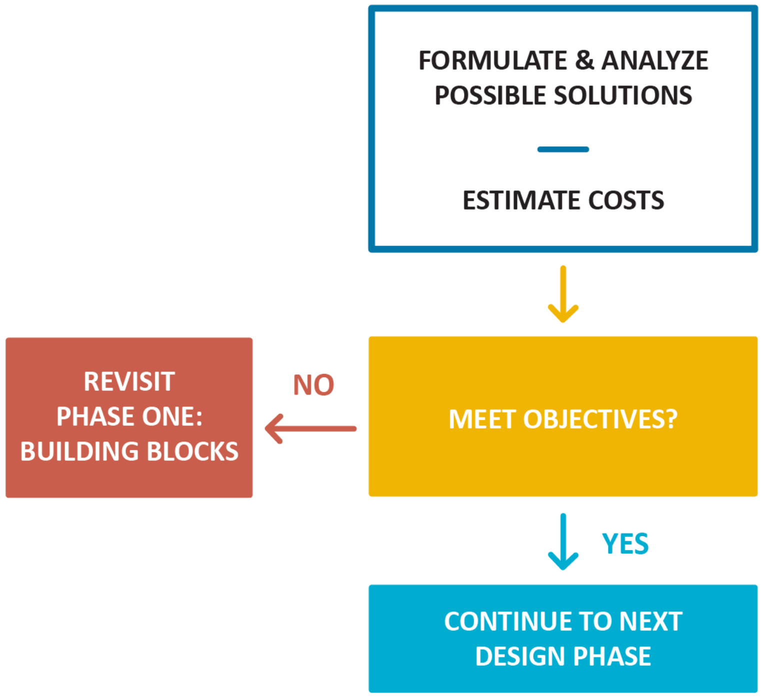


Figure 18: Phase 2, designing a solution

FORMULATE A POSSIBLE SOLUTION "CONCEPT 1"

This module provides guidance on how to formulate and evaluate initial conceptual design options to meet identified performance objectives for critical services and facilities against a set of DBTs. Formulating options include development of conceptual microgrid designs. Options can also include increasing system resilience, energy efficiency, and use of renewable resources and energy storage devices.

The expected performance improvements of the conceptual design options are then compared with the baseline system performance (without improvements) according to the performance objectives to determine how the conceptual design improves system performance. Advanced optimization and performance tools as discussed in Section 6 can be used to map out the optimized performance versus detailed cost of various options to help evaluate the best set of microgrid options that provide the highest performance at the most reasonable cost.

It is important to keep certain things in mind when conceptualizing a microgrid in an area already populated with grid infrastructure. Optimization of existing configurations can improve efficiencies and reduce costs but can also add costs compared to a greenfield project. To assist in thinking through some of the ways with which one can gain efficiencies and optimize solutions, see **Table 4** for a list of Design Considerations.

Design Considerations for Retrofit Circumstances	
Efficiency Improvements and Load Reconfiguration	Aging infrastructure can provide ample opportunities for efficiency gains, reducing the overall load required to maintain functionality. Similarly, in some microgrid designs, the load demand can be reduced by reconfiguring internal building loads to sectionalize critical and non-critical loads within the building so that the microgrid is only required to supply a portion of building loads rather than entire building loads.
Load Shedding	In some microgrid designs, isolation devices can isolate less critical loads within a microgrid when sufficient generation is not available to meet all the load within the microgrid. Loads can be shed by installing remotely operable main breakers on the incoming building feeds.
New Feeders	In some cases, it may be more economical to install a new dedicated microgrid feeder connecting critical loads together rather than use the existing utility grid because the amount of non-critical load far exceeds the critical load (so it would be cost prohibitive to use the existing utility grid to form a microgrid).
Feeder Reconfiguration	Instead of installing a new dedicated microgrid feeder, it may be possible to reconfigure the connections of an existing utility feeder so that critical loads are on the microgrid feeder and the non-critical loads are on other feeders; the existing feeder can be made into a microgrid without a prohibitively large amount of generation required to meet loads.

Table 4: Design Considerations for Retrofit Circumstances

START TO **FORMULATE AND ANALYZE SOLUTIONS**

Evaluate:

- Site and label generation sources and capacity goals
- Look at clusters of facilities/services that might yield higher resilience opportunities (economies of scale, impacting the most users with a single microgrid)
- Sketch proposed feeders and switch locations
- Estimate DER options, consider fuel, assess equipment types and quantities

ESTIMATING UP-FRONT COSTS

Based on a survey done in 2018, Microgrids in the Continental U.S. average [21]:

$2M to $5M / per MW

This section walks through the process of estimating construction costs using average unit prices and quantities established in the previous steps. This step enables communities to account for the costs associated with typical microgrid construction projects. The numbers and rules of thumb included below come from various sources including published cost curves [10] as well as observations and case studies. Note that each project's cost structure will vary as a function of location, size, and complexity. The purpose of this module is to account for the up-front financial investment necessary to build the project. Note that the engineering and construction cost of a microgrid is just one component and is the focus of this section. But the overall *value* of the project for its full lifecycle includes additional factors and timeline considerations. Business models are discussed in the following section.

Basic cost estimates should include:

- *Design and Engineering* - survey the electrical system, do supporting analysis, and create plans. Includes environmental compliance documents, permit applications, as well as engineering oversight during construction.
- *Construction* – equipment, installation, and permitting

It is also valuable to consider:

- *Operation and Maintenance (O&M) Costs* – fuel costs, calibration, and preventative maintenance, planned spare parts, labor, etc. distributed over the life of the installation
- *Retirement and Disposal*

It is reasonable to estimate engineering, permitting, and construction cost as a percentage of a microgrid configuration and its associated equipment. Once the base equipment costs are estimated, the consulting and labor costs are added to determine the overall base costs to build the project. The construction and management oversight costs are estimated to be ~20% of the overall equipment costs. The engineering and design costs are estimated to be ~12.5% of each of the construction equipment costs. These are approximate values based on past projects. A 25% contingency is included to account for the lack of complete information at the conceptual design level. Therefore, the cost estimate approach is:

- Calculate equipment, installation, and labor costs – construction baseline costs (C)
- Calculate additional construction management costs (0.2*C)
- Calculate design cost and engineering cost (0.125*C)
- Sum the overall design, construction, and engineering costs and multiply by 0.25 to get ranges of costs

Example (<u>does not include O&M</u>, which is spread over the life of the asset):

Component	Example Formula	Cost (K)
Equipment (procured and installed)	Given	$1,000
Construction Management	20% of Equipment	$200
Design and Engineering	12.5% of Equipment	$125
Total		**$1,500**

Cost estimates for electrical equipment and labor can be determined using the following:

- Electrical equipment and installation cost data can be obtained with estimate resources such as RS Means[5]
- For equipment not included in these estimates, published reports or equipment manufacturers can be consulted for additional cost information
- Regional Davis-Bacon labor wage rates can be used to modify the basic installation costs for the equipment
- An additional labor productivity adjustment of 15% for construction costs is included to account for any additional costs associated with safety and security requirements and training needed to work on city utilities

Cost estimates are often central to the decision-making processes. In the case of a conceptual design, since many of the details of a final design and construction need to be more fully scoped, this approach provides a rough order of magnitude estimate of the likely range of costs associated with the project energy system upgrades identified.

Fun Fact: Microgrid controller costs per megawatt vary significantly based on the complexity of the controller and the microgrid, with a median controller cost of $155k per MW, but a range of $6.2k to $470k per MW. [20]

Some costs vary only slightly across regions. Other costs vary tremendously. Islands, for example, experience far higher costs than the mainland due to regional availability and logistics.

DEVELOP A **COST ESTIMATE** FOR UP-FRONT COSTS

Note that this does not include operation & maintenance, or fuel

Evaluate:

- Cost of equipment including any modifications to the existing system
- Hardware upgrades and controls
- As time permits, evaluate trade-offs and how to maximize return on investment.

[5] https://www.gordian.com/products/rsmeans-data-services/

5. Business Models

The business model designed to support a new microgrid system remains a critical factor in the microgrid's viability. Though the regulation and management of these systems is no doubt a primary driver in their success, this guide focuses primarily on the technical factors including sizing, operational costs, and developing metrics to quantify overall benefits. While we will not be exploring or comparing business models in depth, this section presents a high-level overview and structure discussion.

There are three basic business models in use today:

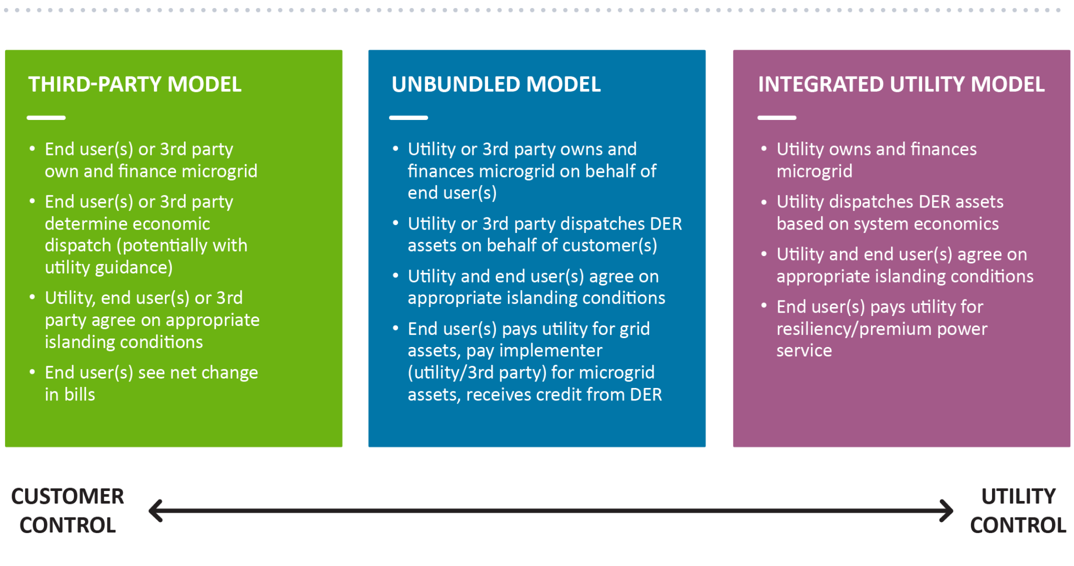


Figure 19: Description of various microgrid operation models in use.

At present, there is no single microgrid business model which is "best" for all cases. End-user ownership still largely dominates the business models in practice, but there are innovative third-party and mixed ownership models that are emerging (**Figure 17**).

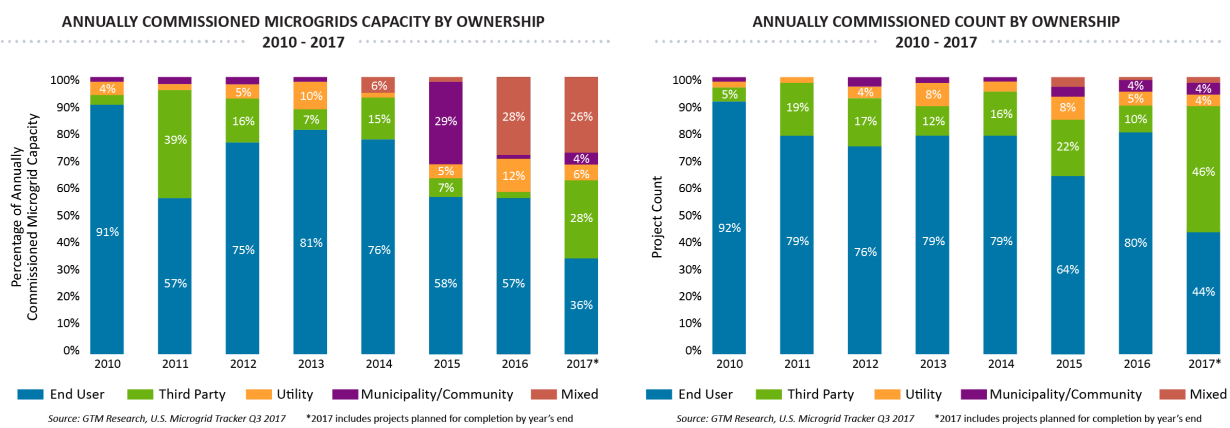
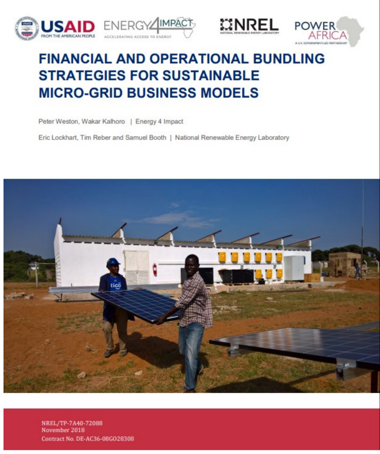


Figure 20: Ownership of Microgrids by Capacity and Count 2010-2017 [10] Case Studies

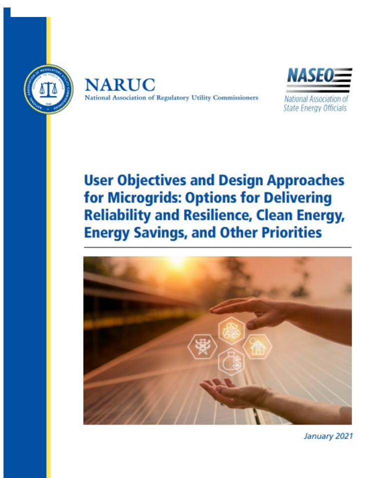
This is an area of significant interest and rapid development. The public domain contains an ever-growing archive of analyses and case studies detailing how various projects have been executed. Three resources that might be useful are referenced here:



Publication: *Financial and Operational Bundling Strategies for Sustainable Microgrid Business Models* [27]

Available through NREL's website: https://www.nrel.gov/docs/fy19osti/72088.pdf

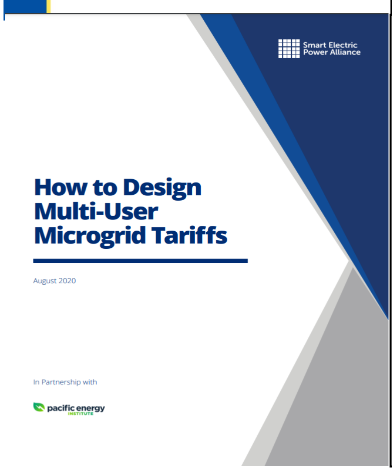
This publication includes a section on Financial Bundling Strategies that may help prospective stakeholders evaluate approaches to funding.



Publication: *User Objectives and Design Approaches for Microgrids: Options for Delivering Reliability and Resilience, Clean Energy, Energy Savings, and Other Priorities* [28]

Available at NARUC's website: https://pubs.naruc.org/pub/E1F332D4-155D-0A36-31CB-889ABED753D5

This publication contains complementary, in-depth discussion related to most of this guidebook. It goes into greater detail of the challenges associated with interconnection and how these affect business decisions.



Publication: *How to Design Multi-User Microgrid Tariffs* [29]

Available online: https://gridarchitecture.pnnl.gov/media/white-papers/SEPA-PEI_How_to_Design_Multi-User_Microgrid_Tariffs.pdf

This publication discusses microgrid tariffs that enable multi-user microgrids to increase the resilience of a community or a small group of customers.

6. Tools

Included here are some, not all, tools available to communities for modeling and simulation of power systems and microgrid solutions.

Microgrid Design Toolkit (MDT) The MDT is a decision-support tool that aids microgrid planners and designers in quantitative analysis to meet objectives and constraints for efficiency, cost, reliability, and environmental emissions. https://www.sandia.gov/csr/center-for-systems-reliability/tools/mdt/	**Technology Management Optimization (TMO)** TMO software optimizes user-defined problems using a genetic algorithm. It can be used to determine optimal design for power generation and distribution systems. https://www.sandia.gov/csr/center-for-systems-reliability/tools/tmo/
ReNCAT Resilience Node Cluster Analysis Tool (ReNCAT) sites microgrids for optimal cost versus social burden performance subject to outage conditions. Not yet publicly available, contact this group for more information: https://energy.sandia.gov/programs/electric-grid/renewable-energy-integration/	**The Distributed Energy Resources Customer Adoption Model (DER-CAM)** DER-CAM answers several important questions related to optimal DER solutions for microgrids including: the optimal portfolio, the ideal installed capacity, energy bill considerations, where in distributed energy resources should be installed and how should they be operated to ensure voltage stability, and what is the optimal DER solution that minimizes costs while ensuring resilience targets. https://gridintegration.lbl.gov/der-cam
EPRI's Open DSS Power distribution system simulation and analysis. https://smartgrid.epri.com/SimulationTool.aspx	**GridLab-D** Power distribution system simulation and analysis https://www.gridlabd.org/

System Advisor Model (SAM) Techno-economic software model that facilitates decision-making. Can model renewable energy systems and their financials. https://sam.nrel.gov/	**Energy Transitions Playbook** Information and resources to help you initiate, plan, and complete an energy transition that relies on local resources and eliminates dependence on imported fuels. https://www.eere.energy.gov/islandsplaybook/
REOpt Techno-economic design support platform to optimize energy systems. Recommends optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, and energy performance goals. https://reopt.nrel.gov/	

Appendix A: Example Microgrid Sequence of Operation

For the purposes of understanding, maintaining, and ensuring adequate functionality of a microgrid, it can be informative to go through the steps associated with its sequence of operation. To aid in this effort, we have developed a generic example representing a theoretical simple Type 3 microgrid with local generation to support only its critical loads.

Given:

- The microgrid predominantly operates grid-tied but can be isolated during main grid outages or other grid events such as high time-of-use rates.
- When the microgrid is isolated, dispatchable generators come online to pick up loads and restore power.
- Isolation devices remove non-critical loads from the microgrid when it is islanded from the main grid.
- There is no energy storage on the microgrid. Any critical loads requiring UPS are assumed to be already provided for in the existing buildings.

Summary Overview of the Sequence

Figures A-1 through A-4 illustrate the basic steps involved in forming an islanded microgrid when starting with a grid-tied collection of buildings. The first step **(Figure A-1)** illustrates a feeder with a microgrid, where a PCC, or main breaker, divides the upstream non-microgrid portion of the feeder from the downstream microgrid portion of the feeder. The microgrid consists of a collection of mission-critical loads and the buildings in which they are housed shown in blue, and non-critical loads shown in yellow. Some buildings have DERs attached to them. In many cases, the generation resources are de-energized when the microgrid is grid-tied. Initially, the PCC is closed, allowing both critical and non-critical loads to be fed from the main grid by the utility.

In step 2 **(Figure A-2)**, when the feeder loses power due to a main grid outage, the microgrid becomes de-energized. Next, the microgrid main breaker (PCC) opens to isolate the microgrid portion of the feeder from the main substation to prevent the generation in the microgrid from back-feeding upstream faults in the utility system for safety purposes. The PCC also sends signals to open non-critical building feeds to prevent them from connecting to the microgrid when the microgrid is islanded to ensure that the microgrid generation can meet all the critical loads. A more sophisticated microgrid control scheme could allow non-critical loads to remain in service if sufficient generation is available. Immediately after the main grid outage, as the microgrid generation resources are being started (~30 seconds), all microgrid critical loads will be without power, so any uninterruptable loads will need backup sources such as UPS units.

In step 3 **(Figure A-3)**, the generators start up to pick up their individual buildings' loads.

Finally, in step 4 **(Figure A-4)**, the generators are synchronized sequentially to the microgrid portion of the feeder until all the generators are connected and all critical loads in the microgrid are provided with power, with each generator output increasing as needed as they are synchronized to larger loads. At this point, the amount of generation provided by the generation resources can be adjusted for more efficient utilization, either manually or through an automated process. For example, if the total microgrid load does not require one or more of the DERs to be available, they can be shut off to make the other resources more fuel efficient.

When main grid power is restored, the steps to undo the microgrid occur in the reverse order. When the power returns, the generation resources at each building sense that power is restored and are individually offloaded from the microgrid in a seamless fashion, preventing any load interruptions. When all critical loads are up and running a signal is sent to the non-critical loads to close their isolation devices and re-energize these buildings.

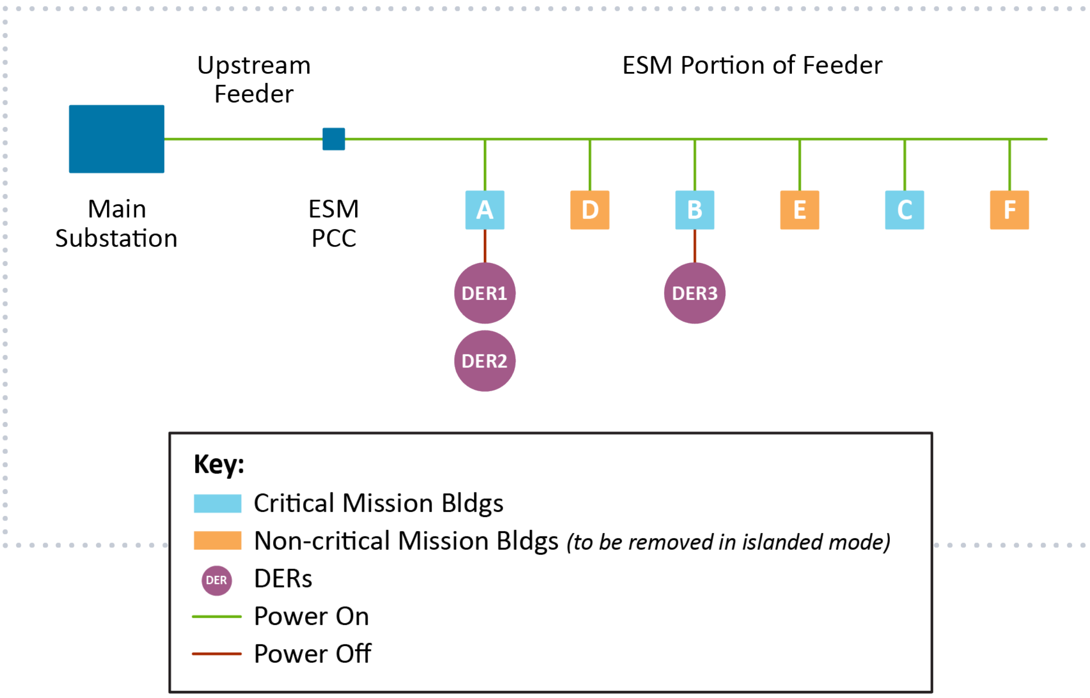


Figure A-1: Grid tied collection of assets during "blue sky" conditions (DER – generation resource such as diesel or gas generator).

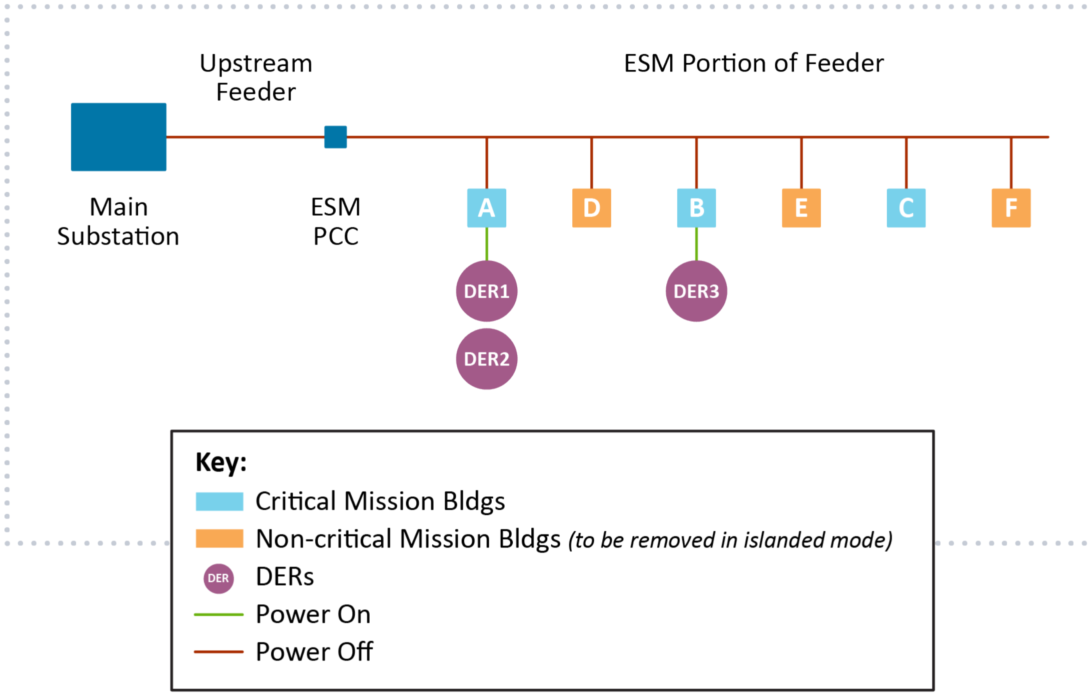


Figure A-2: Step 2 - Loss of utility power to feeder and microgrid (ESM)

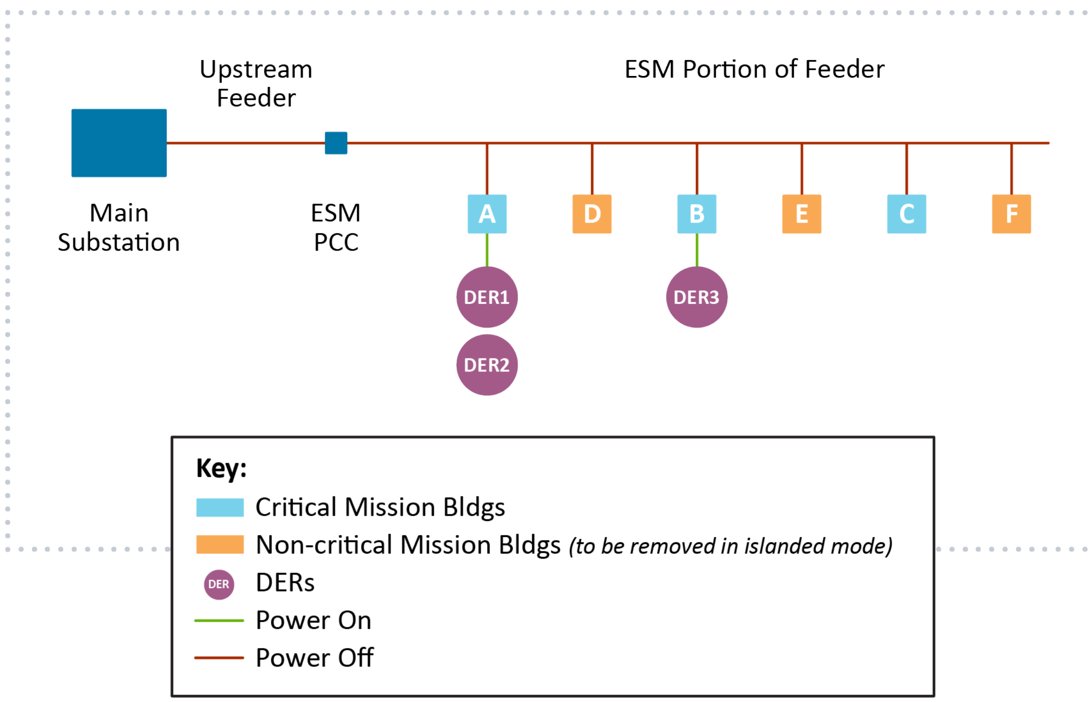


Figure A-3: Step 3 – Generation resources (DERs) start up to pick up critical loads; non-critical loads are kept offline

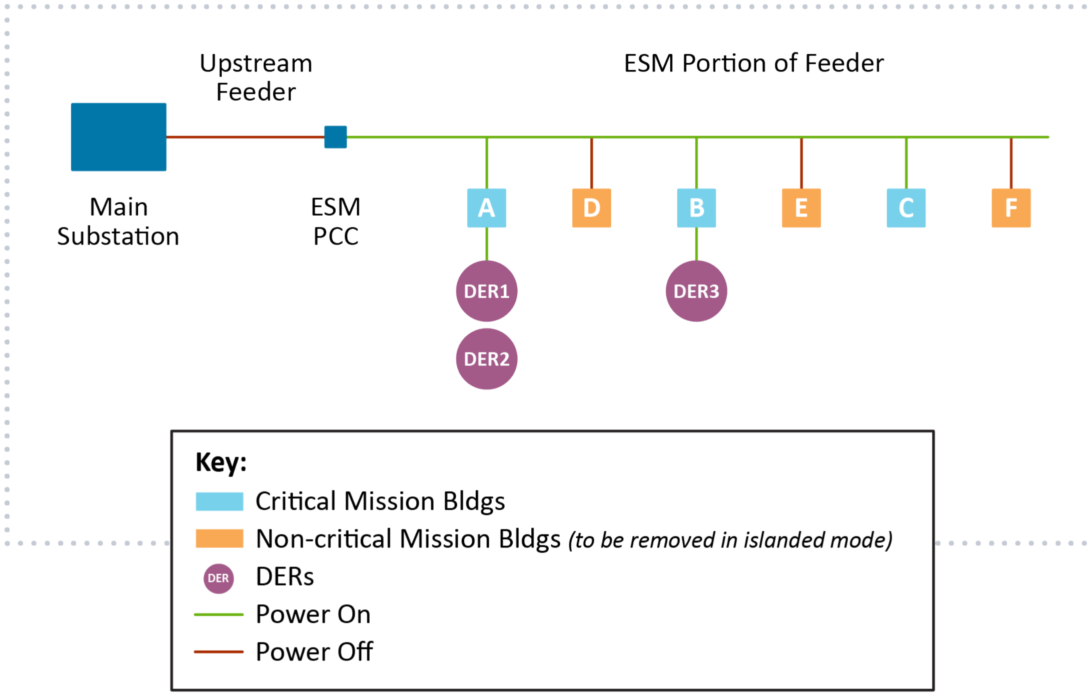


Figure A-4: Step 4 – Generation resources sync together to form microgrid supporting critical loads

A more detailed set of steps for the microgrid to transition from grid-tied to islanded mode and back again is listed below (note, as mentioned, a microgrid may have more than one main breaker/PCC depending on the arrangement):

1. Main grid power is lost, fault clearing devices upstream of the microgrid turn off power; all DERs are taken off the grid (to avoid energizing lines which may be worked on as part of power restoration efforts).
2. The microgrid main breaker (PCC) senses a power loss and opens, islanding the microgrid.
3. The main breaker sends a signal to each building to open main breakers to non-critical loads and receives confirmation that breakers are off (15-45 seconds).
4. Each generation resource's automatic transfer switch (ATS) determines that there has been a loss of utility power.
5. Each ATS starts the generation resources in isochronous mode to pick up their local loads (30-60 seconds, depending on the generator type).
6. Microgrid controls allow each ATS to communicate its status with others.
7. Voltage and frequency are measured at each ATS and communicated to other ATSs in the microgrid.
8. When the voltage and frequency between two ATSs are within a window (i.e., they are in sync), the bypass switch on the ATS is closed (30-60 seconds for all generators to sync together).
9. The generators go into a frequency droop mode, in which the predetermined power and voltage setpoints are altered based on the generator size (percent droop) and are controlled by the microgrid generator controls unless the user changes the setpoints from the main microgrid control algorithms.
10. All the generators will run together as long as the microgrid network provides the correct generator frequency.

11. Renewable resources (if any) may reconnect to the microgrid at this point – isolation devices will reclose and be available for the microgrid
12. At some point, the main power returns and its fault device is cleared, restoring power to the feeder with the microgrid.
13. Controls are used to change the frequency of the generators to match the grid.
14. When the synchronizing conditions are satisfied, the main microgrid breaker (PCC) closes, restoring grid power to the critical loads in the microgrid from the utility.
15. Generators will soft unload and eventually stop.
16. The closed main breaker (PCC) sends signals to close the isolating devices and restore power to all non-critical loads.

It is also possible, in certain situations, to have a microgrid with generation resources normally operating in parallel with the utility (grid-tied), or a microgrid which is normally isolated from the power grid, but which can connect to the grid when needed. The main difference between this example, and a microgrid operated normally in parallel, would be that designated generation resources would be continually operating while connected to critical load. In Step 1 **(Figure A-1),** when utility loads become disconnected, the generation resources will continue to feed critical loads without interruption, but the rest of the steps to form the isolated microgrid will occur. There may be generation resources which are normally off in grid-tied mode but start up to be available only when the microgrid is islanded. As before, if sufficient generation is supplied to the microgrid, non-critical loads will not have to be isolated.

Appendix B: Example Ranking of Critical Infrastructure

ENERGY TRANSITIONS INITIATIVE
U.S. Department of Energy

Handout 3: Powering Critical Infrastructure

Assign the following general services and facilities high, medium, or low priorities. Assign each facility a category of service (e.g., grocery stores apply to the category of "Food" service) to help map facility priorities to service priorities.

	Service	Tolerance (hours)	Priorities (H, M, L)
1	**Communications**	**<1 day**	**H**
2	**Medicine/Supplies**	**<1 day**	**H**
3	**Ambulance**	**<1 hour**	**H**
4	**Fire response**	**<1 hour**	**H**
5	**Road Clearing**	**days**	**M**
6	**Clean water**	**<1 day**	**H**
7	**Food**	**<3 day**	**H**
8	**Wastewater**	**<1 day**	**H**
9	**Flood Control**	**days**	**M**
10	**Shelter**	**<1 day**	**H**
11	**Trash collection**	**Many days**	**L**
12	**Police**	**<1 day**	**H**
13	**Mail delivery**	**Many days**	**L**
14	**Hospital**	**<1 hour**	**H**
15	**Heating/Cooling**	**days**	**M**
16	**Transportation**	**days**	**M**
17	**Fuel**	**<2 day**	**H**
18	**ATMs/money**	**days**	**M**

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